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SECOND QUARTERLY TECHNICAL REPORT - 2430-2  
1 July to 30 September 1967

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DEPUTY FOR SURVEILLANCE AND CONTROL SYSTEMS  
ELECTRONIC SYSTEMS DIVISION  
AIR FORCE SYSTEMS COMMAND  
UNITED STATES AIR FORCE  
L. G. Hanscom Field, Bedford, Massachusetts

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(Prepared under Contract No. AF 19(628)-67-C-0308 by The Ohio State  
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## FOREWORD

This report, OSURF report number 2430-2, was prepared by The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering, 1320 Kinnear Road, Columbus, Ohio. Research was conducted under Contract F 19628-67-C-0308. Lt. Nyman was the Electronic Systems Division Program Monitor for this research. This report covers the period from 1 July to 30 September 1967.

This technical report has been reviewed and is approved.

BERNARD J. FILLIATREAU  
Contracting Officer  
Space Defense System Program Office

## ABSTRACT

This report describes the progress accomplished in the past quarter on the direct-scattering computer program, its anticipated capabilities and limitations, the mathematical description of the target, the physical-optics formulation, and recommendations for subsequent computer program improvement effort.

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## LIST OF SYMBOLS

$(r, \theta, \phi)$	spherical coordinates for a point on the target
$(r_i, \theta_i, \phi_i)$	spherical coordinates of the source of the incident wave
$(r_s, \theta_s, \phi_s)$	spherical coordinates of the receiving antenna
$(\hat{r}, \hat{\theta}, \hat{\phi})$	unit vectors at a point on the target
$(\hat{r}_i, \hat{\theta}_i, \hat{\phi}_i)$	unit vectors at the source of the incident wave
$(\hat{r}_s, \hat{\theta}_s, \hat{\phi}_s)$	unit vectors at the receiving antenna
$F(\rho, z)$	equation for the target surface
$A_l(I)$	coefficients in the equation for section I of the target
$\hat{n}$	unit normal vector on target surface
$ds$	increment of surface area on target
$\underline{r}$	vector from origin to a point on the target surface
$\underline{E}^i$	incident electric field vector
$E_{\theta}^i, E_{\phi}^i$	components of the incident electric field vector
$\underline{E}^s$	scattered electric field vector
$E_{\theta}^s, E_{\phi}^s$	components of the scattered electric field vector
$S_{ij}$	elements in the scattering matrix
$\lambda$	free-space wavelength
$k$	$2\pi / \lambda$
$\underline{A}(w)$	projected area function
$f$	frequency
$t$	time

$\omega$	$2\pi f$
$T$	$1/f$
$c$	speed of light
$F(t)$	pulse-response waveform
$u(x)$	unit step function
$j$	$\sqrt{-1}$

## I. GOALS

Our purpose is to develop new theoretical and computational techniques for electromagnetic scattering. The end result will be a digital computer program designed to calculate the scattering properties of a wide class of targets.

## II. INTRODUCTION

Obviously there would be many applications for a computer program that would permit rapid and accurate calculations of the scattering properties of every conceivable target size, shape and material in the bistatic situation with an incident plane wave having any given polarization, propagation direction, and waveform. However, the current state of the art in scattering theory and computer technology is such that high accuracy, speed and generality are mutually exclusive. Therefore, our objective is to develop a computer program with suitable tradeoffs to permit reasonably accurate calculations with as much speed and generality as is feasible. Since the computer program will be applied primarily to problems where high-frequency scattering theories are appropriate, such techniques as physical optics and the geometrical theory of diffraction are most suitable.

The physical optics technique yields reasonably accurate scattering data in many cases, and yet it permits rapid calculations for a wide class of targets. Furthermore, improved accuracy can be obtained by making a fairly simple modification to the physical optics solution (to remove the erroneous contribution from the shadow boundary) and including the effects of creeping waves which travel around the shadowed region of the target.

The following sections in this report describe our progress with the creeping-wave approach during the past quarterly period, set forth the probable capabilities and limitations of the final computer program, and present the equations for the physical-optics formulation. Finally, recommendations are given for subsequent improvements that should be made in the computer program toward greater accuracy and wider applicability.

## III. PROGRESS WITH THE CREEPING-WAVE APPROACH

A computer subroutine for wedge diffraction coefficients was obtained from another group at this Laboratory. This program computes the far-zone scattered field of a wedge with arbitrary included

angle. The logic for determining which wedges on the target contribute to the back-scattered field was written but has not yet been tested.

The subroutines for determining the radii of curvature, differential arc length, and Gaussian curvature at an arbitrary point on the target have been written and tested for spheres, spheroids and ogives.

The numerical integration subroutine for the path lengths of the creeping waves has been written. The subroutine for determining the specular point and the attachment and reradiation points of the creeping wave is being tested.

These subroutines will next be combined to compute the backscatter from bodies of revolution for parallel polarization. The case of perpendicular polarization will require further development of a subroutine for determining the creeping wave paths.

The theoretical basis for the creeping-wave approach is presented in Reference 1.

#### IV. COMPUTER PROGRAM CAPABILITIES

This section sets forth the anticipated capabilities and limitations of the computer program which will be the end product of this effort. Some of the limitations could be eliminated with the one-year follow-up program recommended in Section VII.

Figure 1 shows a general flow chart for the computer program.

The program will handle perfectly conducting targets. The surface is considered to be convex and continuous. The target may have any size, but the accuracy of the output data will be doubtful when the target is too small in comparison with the wavelength, and the computation time and memory storage requirements will increase for large targets.

The effects of antennas mounted on or in the target will not be calculated. The effects of fins will not be considered, with the possible exception of fins on a body of revolution for the CW backscatter case.

Bistatic scattering data will be calculated with the physical-optics technique for the CW and pulse cases. In the pulse case, there will be no limitations on the pulse length aside from the requirement that

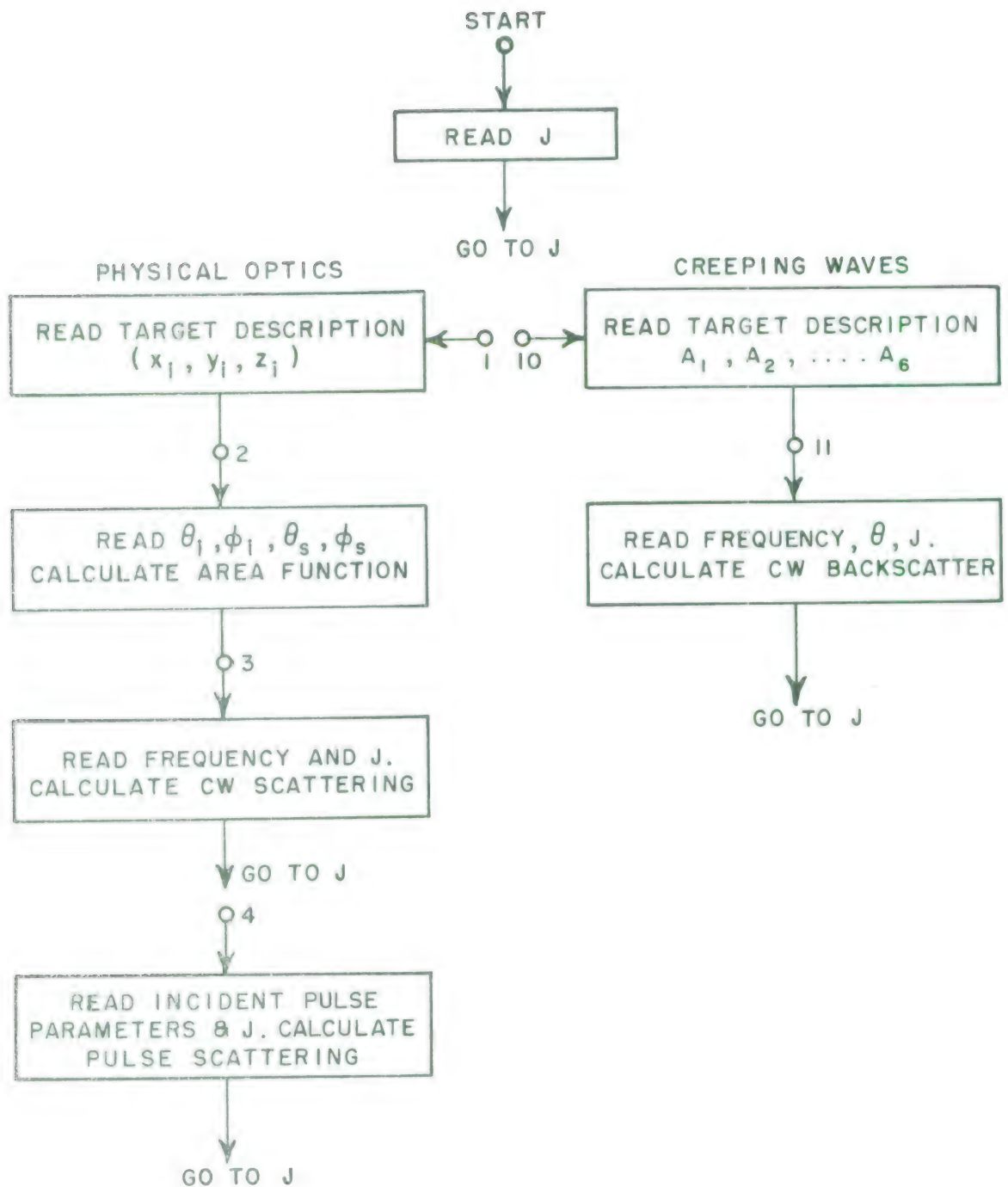


Fig. 1. General flow chart for the computer program.

the incident pulse have  $M$  complete cycles (where  $M$  is an integer). The incident wave is considered to be an amplitude-modulated carrier with a square-wave modulation envelope.

The creeping wave contributions will be calculated to yield greater accuracy for CW backscatter from bodies of revolution. The off-diagonal elements in the scattering matrix will be set equal to zero in backscatter problems, since a better solution is not feasible at this time.

The direct-scattering computer program will not calculate the Doppler frequency shifts associated with target motion, coordinate transformations between the target-fixed reference frame and other reference frames, or the time and phase delays associated with the distances from the target to the transmitting and receiving antennas.

## V. TARGET DESCRIPTION

For physical-optics calculations, the target will be described in terms of a large number of points  $(x_i, y_i, z_i)$  on the surface. These points will lie on the intersections of the target surface with the planes  $z = z_1, z = z_2, \text{ etc.}$  The coordinate origin will be located in the interior of the target. The target surface will be approximated by triangular facets with vertices at the given points. It will be assumed that the points will cover the surface with a density such that each facet is small in comparison with the wavelength.

The creeping-wave analysis will be programmed for backscatter data for perfectly conducting bodies having axial symmetry with respect to the  $z$  axis. The coordinate origin will be located in the interior of the target. The surface will have  $N$  analytic subsurfaces with boundaries defined by the intersections with the cones  $\theta = \theta_i$ . Subsurface  $I$  will be described by a set of six real coefficients  $A1(I), A2(I), \dots, A6(I)$  in accordance with the following equation:

$$(1) \quad F(\rho, z) = A1(I) \rho^2 + A2(I) z^2 + A3(I) \rho z + A4(I) z + A5(I) \rho + A6(I) = 0$$

where  $\rho$  denotes the radial coordinate in the cylindrical system. Thus, the trace of each subsurface on the  $xz$  plane will be a conic section.

## VI. THE PHYSICAL OPTICS FORMULATION

If the transmitting antenna is at a great distance from the target, it will illuminate the target with an incident field which is essentially a plane wave. In the CW case we let the time dependence  $e^{j\omega t}$  be understood and represent the incident electric field intensity as follows:

$$(2) \quad \underline{E}^i = (\hat{\theta}_i E_{\theta}^i + \hat{\phi}_i E_{\phi}^i) e^{jk \hat{r}_i \cdot \underline{r}}$$

where  $(r_i, \theta_i, \phi_i)$  are the spherical coordinates of the transmitting antenna,  $(\hat{r}_i, \hat{\theta}_i, \hat{\phi}_i)$  are the corresponding unit vectors,

$$(3) \quad k = 2\pi/\lambda,$$

$\lambda$  denotes the wavelength, and  $E_{\theta}^i$  and  $E_{\phi}^i$  are complex constants. An arbitrary point on the target surface is assigned the coordinates  $(r, \theta, \phi)$ , the unit vectors  $(\hat{r}, \hat{\theta}, \hat{\phi})$ , and the position vector

$$(4) \quad \underline{r} = r \hat{r}$$

Finally, the receiving antenna is assigned the coordinates  $(r_s, \theta_s, \phi_s)$  and the unit vectors  $(\hat{r}_s, \hat{\theta}_s, \hat{\phi}_s)$ . Thus  $\theta_i$  and  $\phi_i$  specify the incidence angles and  $\theta_s$  and  $\phi_s$  are the scattering angles. The magnetic field intensity of the incident plane wave is given by

$$(5) \quad \underline{H}^i = (\hat{\theta}_i E_{\phi}^i - \hat{\phi}_i E_{\theta}^i) \frac{e^{jk \hat{r}_i \cdot \underline{r}}}{\eta}$$

where

$$(6) \quad \eta = \sqrt{\mu/\epsilon}.$$

The current density induced on the illuminated portion of the target surface is approximated as follows:

$$(7) \quad \underline{J} = 2\hat{n} \times \underline{H}^i$$

where  $\hat{n}$  denotes the outward unit normal vector on the surface. The vector potential for the distant scattered field is given by

$$(8) \quad \underline{A} = \frac{\mu}{4\pi r_s} e^{-jkr_s} \int \int \underline{J} e^{jk\hat{r}_s \cdot \underline{r}} ds$$

At a great distance from the target, the scattered field is

$$(9) \quad \underline{E}^s = -j\omega \underline{A} = -\frac{j\omega\mu}{2\pi r_s} e^{-jkr_s} \int \int \hat{n} \times \underline{H}^i e^{jk\hat{r}_s \cdot \underline{r}} ds$$

From Eqs. (5) and (9),

$$(10) \quad \underline{E}^s = \frac{e^{-jkr_s}}{r_s} (\hat{\theta}_i E_{\phi}^i - \hat{\phi}_i E_{\theta}^i) \times \underline{S}$$

where

$$(11) \quad \underline{S} = (j/\lambda) \int \int \hat{n} e^{jk(\hat{r}_i + \hat{r}_s) \cdot \underline{r}} ds$$

The distant scattered field is represented by

$$(12) \quad \underline{E}^s = (\hat{\theta}_s E_{\theta}^s + \hat{\phi}_s E_{\phi}^s) \frac{e^{-jkr_s}}{r_s}$$

where  $E_{\theta}^s$  and  $E_{\phi}^s$  denote complex constants. From Eqs. (10) and (12) and the following vector identity,

$$(13) \quad \underline{A} \cdot (\underline{B} \times \underline{C}) = (\underline{A} \times \underline{B}) \cdot \underline{C} \quad ,$$

it is found that

$$(14) \quad E_{\theta}^s = (E_{\theta}^i \hat{\phi}_i \times \hat{\theta}_s + E_{\phi}^i \hat{\theta}_s \times \hat{\theta}_i) \cdot \underline{S}$$

and

$$(15) \quad E_{\phi}^s = (E_{\theta}^i \hat{\phi}_i \times \hat{\phi}_s + E_{\phi}^i \hat{\phi}_s \times \hat{\theta}_i) \cdot \underline{S}$$

It is convenient to define the CW scattering matrix as follows:

$$(16) \quad \begin{pmatrix} E_{\theta}^s \\ E_{\phi}^s \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} E_{\theta}^i \\ E_{\phi}^i \end{pmatrix}$$

From Eqs. (14) through (16), the complex elements in the scattering matrix are given by

$$(17) \quad S_{11} = (\hat{\phi}_i \times \hat{\theta}_s) \cdot \underline{S}$$

$$(18) \quad S_{12} = (\hat{\theta}_s \times \hat{\theta}_i) \cdot \underline{S}$$

$$(19) \quad S_{21} = (\hat{\phi}_i \times \hat{\phi}_s) \cdot \underline{S}$$

$$(20) \quad S_{22} = (\hat{\phi}_s \times \hat{\theta}_i) \cdot \underline{S}$$

It is convenient to define a "vector area function"  $\underline{A}(w)$  as follows:

$$(21) \quad \underline{S} = (j/\lambda) \int \underline{A}(w) e^{j\beta w} dw ,$$

where

$$(22) \quad w = \frac{(\hat{r}_i + \hat{r}_s) \cdot \underline{r}}{|\hat{r}_i + \hat{r}_s|}$$

and

$$(23) \quad \beta = k |\hat{r}_i + \hat{r}_s| .$$

It may be seen from Eq. (22) that  $w$  represents one of the coordinates of a point on the target surface, in a rectangular coordinate system that is rotated in space with respect to the  $(x, y, z)$  system. The  $w$  axis is coplanar with  $\hat{r}_i$  and  $\hat{r}_s$  and bisects the angle between these unit vectors.

For any point  $(x, y, z)$  on the target surface,

$$(24) \quad w = \left[ x(\sin\theta_i \cos\phi_i + \sin\theta_s \cos\phi_s) + y(\sin\theta_i \sin\phi_i + \sin\theta_s \sin\phi_s) + z(\cos\theta_i + \cos\theta_s) \right] \frac{1}{|\hat{r}_i + \hat{r}_s|} ,$$

where

$$(25) \quad \left| \hat{r}_i + \hat{r}_s \right| = \left[ (\sin\theta_i \cos\phi_i + \sin\theta_s \cos\phi_s)^2 + (\sin\theta_i \sin\phi_i + \sin\theta_s \sin\phi_s)^2 + (\cos\theta_i + \cos\theta_s)^2 \right]^{\frac{1}{2}}$$

Once the vector area function has been calculated,  $\underline{S}$  can be determined efficiently from Eq. (21) by numerical integration. Equation 11 would take more computation time since it involves a surface integral instead of a line integral.

Once  $\underline{S}$  has been calculated, the elements in the scattering matrix are determined as follows:

$$(26) \quad S_{11} = S_x X_{11} + S_y Y_{11} + S_z Z_{11}$$

$$(27) \quad S_{12} = S_x X_{12} + S_y Y_{12} + S_z Z_{12}$$

$$(28) \quad S_{21} = S_z Z_{21}$$

$$(29) \quad S_{22} = S_x X_{22} + S_y Y_{22} + S_z Z_{22}$$

where

$$(30) \quad \underline{S} = \hat{x} S_x + \hat{y} S_y + \hat{z} S_z$$

$$(31) \quad X_{11} = -\cos\phi_i \sin\theta_s$$

$$(32) \quad Y_{11} = -\sin\phi_i \sin\theta_s$$

$$(33) \quad Z_{11} = -(\sin\phi_i \sin\phi_s + \cos\phi_i \cos\phi_s) \cos\theta_s$$

$$(34) \quad X_{12} = \cos\theta_i \sin\phi_i \sin\theta_s - \sin\theta_i \cos\theta_s \sin\phi_s$$

$$(35) \quad Y_{12} = \sin\theta_i \cos\theta_s \cos\phi_s - \cos\theta_i \cos\phi_i \sin\theta_s$$

$$(36) \quad Z_{12} = (\sin\phi_i \cos\phi_s - \cos\phi_i \sin\phi_s) \cos\theta_i \cos\theta_s$$

$$(37) \quad Z_{21} = \cos\phi_i \sin\phi_s - \sin\phi_i \cos\phi_s$$

$$(38) \quad X_{22} = -\sin\theta_i \cos\phi_s$$

$$(39) \quad Y_{22} = -\sin\theta_i \sin\phi_s$$

$$(40) \quad Z_{22} = -(\cos\phi_i \cos\phi_s + \sin\phi_i \sin\phi_s) \cos\theta_i$$

In the pulse case, the incident wave is considered to have  $M$  complete cycles and a square modulation envelope.  $M$  is assumed to be an integer, and the incident field is expressed by

$$(41) \quad \underline{E}^i = (\hat{\theta}_i E_{\theta}^i + \hat{\phi}_i E_{\phi}^i) \sin(\omega t + k \hat{r}_i \cdot \underline{r}) \cdot \left[ u(\omega t + k \hat{r}_i \cdot \underline{r}) - u(\omega t + k \hat{r}_i \cdot \underline{r} - \omega \tau) \right]$$

where  $E_{\theta}^i$  and  $E_{\phi}^i$  are real constants,  $u(x)$  denotes the unit step function,  $f$  is the carrier frequency,

$$(42) \quad \omega = 2\pi f,$$

$$(43) \quad T = 1/f,$$

and

$$(44) \quad \tau = MT.$$

The scattered field is given by

$$(45) \quad \underline{E}^s(r_s, t) = [\hat{\theta}_s E_\theta^s(t - r_s/c) + \hat{\phi}_s E_\phi^s(t - r_s/c)] \frac{1}{r_s}$$

It is convenient to write the following matrix equation

$$(46) \quad \begin{pmatrix} E_\theta^s(t) \\ E_\phi^s(t) \end{pmatrix} = \begin{pmatrix} F_{11}(t) & F_{12}(t) \\ F_{21}(t) & F_{22}(t) \end{pmatrix} \begin{pmatrix} E_\theta^i \\ E_\phi^i \end{pmatrix}$$

The pulse response of the target is thus defined with four functions of time given by:

$$(47) \quad F_{11}(t) = (\hat{\phi}_i \times \hat{\theta}_s) \cdot \underline{F}(t)$$

$$(48) \quad F_{12}(t) = (\hat{\theta}_s \times \hat{\theta}_i) \cdot \underline{F}(t)$$

$$(49) \quad F_{21}(t) = (\hat{\phi}_i \times \hat{\phi}_s) \cdot \underline{F}(t)$$

$$(50) \quad F_{22}(t) = (\hat{\phi}_s \times \hat{\theta}_i) \cdot \underline{F}(t)$$

where

$$(51) \quad \underline{F}(t) = \frac{1}{\lambda} \int \int \hat{n} \cos(\omega t + \beta w) \cdot [u(\omega t + \beta w) - u(\omega t + \beta w - \omega \tau)] ds$$

Eq. (51) can also be written as follows

$$(52) \quad \underline{F}(t) = \frac{1}{\lambda} \int \underline{A}(w) \cos(\omega t + \beta w) [u(\omega t + \beta w) - u(\omega t + \beta w - \omega \tau)] dw$$

Equation (52) will be employed in the computer program since it permits more rapid calculations than Eq. (51).

The scattering waveforms  $F_{11}(t)$ ,  $F_{12}(t)$ ,  $F_{21}(t)$  and  $F_{22}(t)$  will be calculated at a discrete set of equally spaced points in time. The spacing between these points will be determined by an integer  $L$ , supplied by the operator, as follows

$$(53) \quad \Delta t = T/L$$

The first and last points will coincide with the initiation and the termination of the pulse response.

## VII. RECOMMENDATIONS

A one-year follow-up effort is recommended to increase the accuracy and widen the scope of the direct-scattering computer program. Our recommendations are listed below.

1. The program should be extended to handle imperfectly conducting, absorber-coated, dielectric and composite targets. This could be accomplished with the formulation developed in Reference 2.
2. The scattering effects of antennas mounted on the target should be incorporated in the program. This is believed to be feasible if the input data include the antenna input impedance, the antenna pattern, and the load impedance.
3. The capability of handling fins and concave regions on the target should be developed by using multiple-bounce reflection theory.
4. The creeping-wave subroutines should be generalized to the bistatic case and to targets having no axis of symmetry.
5. An attempt should be made to program an accurate impulse response for targets of arbitrary shape. This might be accomplished by starting with the physical-optics step response

(calculated in the present program) and applying various corrections with the techniques developed by Kennaugh and Moffatt.<sup>3</sup> This impulse response could then form the basis for accurate scattering data even when the incident radar pulse has frequency modulation (as with chirp radar) or amplitude modulation with an envelope more realistic than the square wave.

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